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The impact of indoor environment quality (IEQ) on school children's overall comfort in the UK; a regression approach

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ABSTRACT

Indoor Environment Quality (IEQ) is grouped into four main categories: thermal comfort, indoor air quality (IAQ), visual and acoustic comfort. Individual aspects of IEQ are investigated to examine their impact on children's overall comfort in primary schools in the UK. This study has surveyed 805 children in 32 naturally ventilated classrooms during non-heating and heating seasons. This study has calculated the proportion of comfort votes by individual aspects of IEQ, predicted comfort votes by multilinear regression model and estimated the probability of having uncomfortable votes by binary logistic regression.

Results of this study highlight that the proportion of uncomfortable votes should be kept below 10%. The developed multilinear model suggests that for a unit change in Air Sensation Votes (ASVs) and operative temperatures (T_{op}), comfort votes change by 0.28 and 0.12, respectively. Developed multilinear and logistic regression models show that ASVs have a more significant impact on overall comfort than T_{op}. To achieve acceptable comfortable votes and keep the probability of having uncomfortable votes below 10%, ASVs and T_{op} should be kept within these limits: [ASV = very fresh and T_{op} = 19–27 °C], [ASV = fresh and T_{op} = 19–24 °C], and [ASV = OK and T_{op} = 19–22 °C]. The ranges suggest that better perception of IAQ makes up for higher temperatures. It is advised to maintain individual aspects of IEQ, however, dissatisfaction with one aspect of IEQ does not necessarily result in overall discomfort unless that aspect is extremely unacceptable. Investigating the most influential factors on occupants' comfort suggests which building controls should be prioritized for designers.

1. Introduction

In the 1990s, it was acknowledged that occupant's discomfort and complaints about the indoor environment were not caused by one single parameter [1]. Cao et al. (2012) state that occupants' discomfort reflects the physiological and psychological influences caused by many factors [2]. Indoor Environment Quality (IEQ) depends on many variables such as temperature, relative humidity, air velocity, airflow, the concentration of pollutants, odours, noise and lighting [3]. The concept of Indoor Environment Quality (IEQ) can be grouped into four main categories: thermal comfort, indoor air quality (IAQ), visual comfort and acoustic comfort [4–11].

IEQ is an important factor for comfort [12,13], health and well-being of building occupants [7,13,14]. Poor IEQ results in Sick Building Syndrome (SBS), such as feeling cold, headache, dizziness, confusion, nausea, fatigue, respiratory problems and irritation of eyes, throat, nose and skin [15]. Furthermore, IEQ affects lifecycle costs and energy consumption of buildings significantly [12,14,16–20]. By providing IEQ, indoor comfort conditions would be higher and less energy would be consumed which are primary goals of any building [18,20]. Therefore, its evaluation and quantification should be investigated during the design process [16,17].

The primary purpose of school buildings is to provide children with ideal places for their learning and development [21] as excellence in education is the aim of any modern society [3]. Fry (2008) states that it is essential to provide all comfort aspects in classrooms because the learning process happens through various senses (i.e. listening, speaking and visualizing) [22]. IEQ should be improved to increase productivity and performance [8,12–14,23], otherwise, learning and academic activities may be compromised [8,24–26] through discomfort or distraction [8]. Berner (1993) suggests that students' test scores increased 5.4

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Nomenclatures

Symbols

T_{op}	Operative Temperature
V	Air Speed
CO2	CO 2 level
RH	Relative Humidity
Lux	Light level
Tout	Outdoor temperature
Vout	Outdoor Speed
Hout	Outdoor Humidity
R2	Coefficient of Determination
Logit	Logistic
P-value	Significance of correlation Coefficient
TC(children)	Children's Comfort Temperature
PD	Probability of having uncomfortable votes

Acronyms and Abbreviation

IEQ	Indoor Environment Quality
IAQ	Indoor Air Quality
TSVs	Thermal Sensation Votes
ASVs	Air Sensation Votes
VSVs	Visual Sensation Votes
NV	Naturally Ventilated
S.D.	Standard Deviation
OA	Open Area
YO	Years Old
RSS	Residual Sum of Squares
UGR	Unified Glare Rating
Cor	Correlation
Sig.	Significance

points ($p < 0.05$) for each improved category of building condition (i.e. 'poor' to 'fair' to 'excellent') [27]. De Giuli et al. (2012) studied IEQ in Italian primary schools and revealed very high concentrations of CO_2, insufficient light, uncomfortable thermal conditions, and acoustic discomfort as the main concerns in the studied primary schools [28].

The feeling of comfort is a composite state involving occupants' sensations of all interrelated physical parameters [29–32]. Nagano and Horikoshi (2005) suggest that the purpose of combining different environmental factors is to clarify the individual effects of each factor and their interaction [29]. Therefore, investigating the weight of different aspects of IEQ in schools is significant to improve comfort. Several studies have suggested weights of different aspects of IEQ in educational buildings [15,20,33,34], Table 1.

The study by Yee (2014) evaluates IEQ through factors affecting occupants' perception and preference of the indoor environment. A questionnaire is used as a method to collect primary data in a University building in Malaysia. The five-point Likert scale questions from 40 valid questionnaires were analysed based on the weighted mean. Results show that respondents consider thermal comfort to be most important ($W_{Thermal} = 0.27$), followed by IAQ ($W_{IAQ} = 0.26$), visual comfort ($W_{visual} = 0.24$) and acoustic comfort ($W_{Acoustic} = 0.23$) [15]. The study by Ghita and Catalina (2015) aims to investigate the indoor environmental quality (IEQ) by long term measurements and spot recordings in three different types of rural schools (old, new, and renovated) from autumn 2013–spring 2014 [20]. Each of sub-indexes is given a weight by the means of 708 questionnaire surveys from 112 school children (10–16 YO). Results derived from regression models show that school children consider IAQ to be most important ($W_{IAQ} = 0.3$), followed by thermal comfort ($W_{Thermal} = 0.27$), visual comfort ($W_{Visual} = 0.24$) and acoustic comfort ($W_{Acoustic} = 0.19$) [20]. Mihai and Iordache (2016) have determined an indoor environmental quality index by reference to thermal comfort, acoustic comfort, indoor air quality and visual comfort [33]. Indoor environmental quality Index is calculated as a weighted average of the indices of comfort. The study collects data on the current state of the building, indoor and outdoor environmental parameters and occupants' sensation of comfort on one winter day in university classrooms [33]. The results on 115 questionnaires show that the four analysed comfort components influence comfort feeling almost equally, $W_{IAQ} = 0.26 \approx W_{Thermal} = 0.25 \approx W_{Visual} = 0.24 \approx W_{Acoustic} = 0.22$ [33].

The study by Tahsildoost and Zomorodian (2018) has assessed IEQ in three school buildings (old, new, and retrofitted) in Iran by environmental measurements and questionnaires ($n = 842$) from July 2016 to April 2017 [34]. The study has developed a mathematical model to predict overall comfort by fitting a multiple regression model to the questionnaire data. Results reveal that thermal comfort is the most important aspect ($W_{Thermal} = 0.34$), followed by visual comfort ($W_{Visual} = 0.31$), acoustic comfort ($W_{Acoustic} = 0.26$) and IAQ ($W_{IAQ} = 0.08$) [34].

Several other studies have suggested the most important aspect(s) of IEQ in educational buildings [11,35,36], Table 2. Astolfi and Pellerey (2008) have carried out a subjective survey on perceived environmental quality in 51 secondary-school classrooms in Italy [11]. The questionnaire including items on overall quality and its aspects such as thermal, IAQ, visual and acoustical, was administered to 1006 students [11]. Results show that with the same dissatisfaction for thermal, IAQ and acoustical, students attributed more weight to the acoustical conditions in the overall quality judgment [11]. Ralegaonkar and Sakhare (2014) have developed a comfort model by using multi-parametric regression analysis of the results in a test room model in an educational campus in India [35]. Indoor environmental variables including indoor light intensity, temperature and humidity were recorded from July 2011–March 2012 on an hourly basis [35]. For the developed model, the considered functional parameters are prioritized by relative importance to indoor temperature, relative humidity and daylight [35]. The study by Kim et al. (2017) has developed an integrated IEQ score by combining three different IEQ indices (i.e., IAQ, thermal and visual comfort) [36]. The study has calculated the integrated IEQ score by using the fitness function in integrated multi-objective optimization in an elementary school in Seoul. The study indicates that IAQ has more

Table 1
Studies with weights on IEQ in educational buildings.

Authors and Year of Publication	Ref	Location	Measurements			Methods		Weights			
			Environmental	Sensations	N_{Survey}	Weighted mean	Multiple-regression	Thermal	IAQ	Visual	Acoustic
Yee, 2014	[15]	Malaysia		✓	40	✓		**0.27**	0.26	0.24	0.23
Ghita and Catalina, 2015	[20]	Romania	✓	✓	708		✓	0.27	**0.3**	0.24	0.19
Mihai and Iordache, 2016	[33]	NA	✓	✓	115	✓		0.25	**0.26**	0.24	0.24
Tahsildoost and Zomorodian, 2018	[34]	Iran	✓	✓	842		✓	**0.34**	0.08	0.31	0.26

Table 2
Studies showing the most important aspect of IEQ in educational buildings.

Authors and Year of Publication	Ref	Location	Measurements			Methods		The most important aspect			
			Environmental	Sensations	N_{Survey}	Weighted mean	Multiple-regression	Thermal	IAQ	Visual	Acoustic
Astolfi and Pellerey, 2008	[11]	Italy	✓	✓	1006	✓					✓
Ralegaonkar and Sakhare, 2014	[35]	India	✓		NA		✓	✓			
Kim et al., 2017	[36]	Seoul	✓		NA		✓		✓		

The review of studies in educational buildings suggests below summaries.

influences on the integrated IEQ score than thermal and visual comfort [36].

- The importance and weight of IEQ aspects are different which can be explained by diverse climates, building types and individual differences.
- The most important aspects of IEQ are thermal environment [15,34,35], IAQ [20,33,36] and acoustic environment [11] and the least important aspects are acoustic [15,20] and visual environment [35].
- IEQ index is predicted based on environmental parameters [35–37], sensation votes [15] or a combination of both [11,20,33,34]. Most models consider the combination of both subjective and objective approaches to evaluate IEQ. Otherwise, the interpretation of the results would be incomplete and misleading [38], because the subjective nature of surveys complicates their use as the only tool for evaluating IEQ in buildings [14].
- Only a few studies have considered building-related factors in IEQ models [20,33,37] while most studies do not consider building differences (e.g. ventilation or window type).
- Studies have applied (Multi/non-linear) regression approach [11,20,33–35,37] or weighted mean approach [15,33] to evaluate IEQ or overall comfort.

Very few studies have investigated children's preferences in terms of IEQ or have included children's comfort to improve IEQ in classrooms [39]. Earlier studies by authors have investigated individual aspects of IEQ in schools, such as thermal comfort [40], indoor air quality [41,42] and visual comfort [43], however, the current study deals with a holistic approach to improve overall comfort in relation with IEQ. This study aims to investigate children's overall comfort within individual aspects of IEQ (thermal comfort, IAQ and visual comfort) in naturally ventilated classrooms in the UK. The main objectives of this study are: (1) to suggest the permissible proportion of uncomfortable votes, (2) to develop comfort model by investigating individual aspects of IEQ, (3) to estimate the probability of having uncomfortable votes. Based on the review, overall comfort in relation with IEQ is predicted based on both subjective and objective measurements with a regression approach.

2. Methodology

This paper aims to investigate how children's overall comfort is related to individual categories of IEQ (thermal comfort, IAQ and visual comfort). The main steps carried out in this methodology are 1. Defining Research Design 2. Sampling climate, buildings and occupants 3. Acquiring data on children's sensation votes and environmental measurements 4. Analysing Regression Approach 5. Evaluating IEQ against Standards and 6. Overviewing recorded data. Fig. 1 shows steps carried out in the methodology.

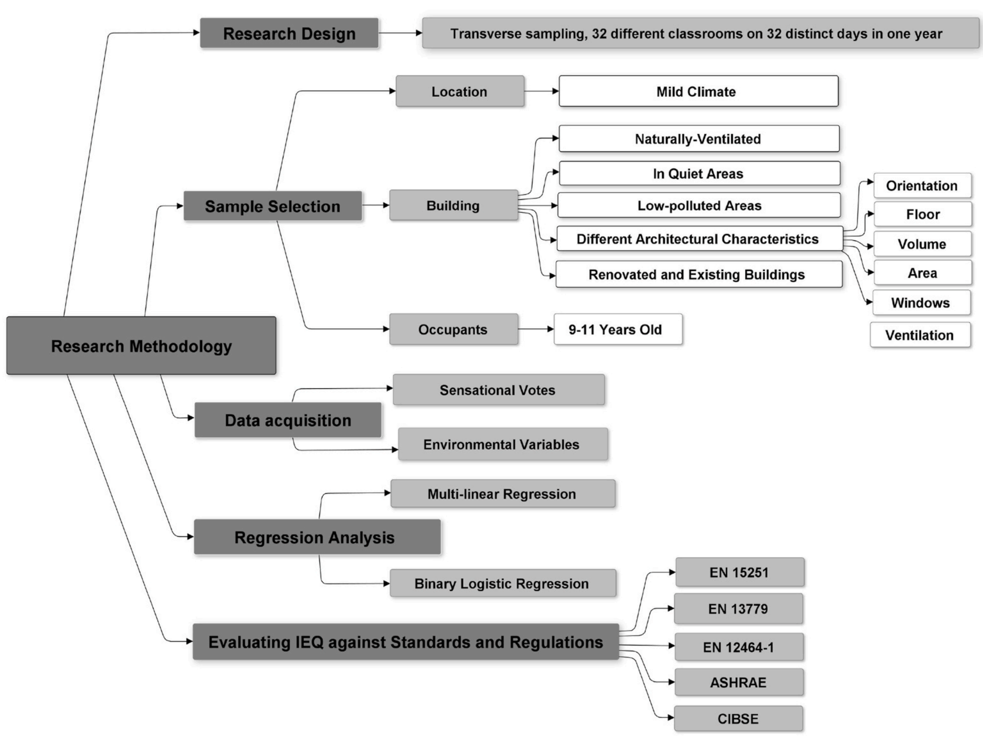

Fig. 1. Research flowchart for methodology.

2.1. Research design

The design of the study defines transverse sampling in which bias is lowered or avoided according to Nicol et al. (2012) [44], therefore, the results are more representative. Longitudinal sampling is not used in this type of study due to many intervening variables during a lengthy time [45], the small population [44] and respondents losing interest in participating due to high frequency of surveys [46]. Hence, data acquisition and observations were carried out in 32 different classrooms on 32 distinct days throughout one year. To increase the validity of the study and reduce bias, the number of studied classrooms is similar during non-heating (n = 16) and heating (n = 16) seasons.

2.2. Sample selection

Samples were selected with specific attention to location, buildings and observed occupants.

2.2.1. Location

Schools were selected in the mild climate of UK because mild climates can provide opportunities for buildings' natural ventilation, as supported in several other studies [47–49] and can reduce the biased impact of one extreme climate on window operation in NV buildings. This study was carried out in Coventry, West Midland from July 2017 until the end of May 2018 to embrace various environmental conditions. Both non-heating and heating seasons were studied because variations in temperature and relative humidity would influence students' perception of the indoor environment [50,51]. Descriptive statistics of outdoor physical variables at the time of filling out the questionnaire are presented in Table 3. Measurements show that outdoor temperatures varied between 11.5 and 24.9 °C with a mean of 18.1 °C during non-heating seasons and changed between 3.5 and 14.2 °C with a mean of 7.8 °C during heating seasons. Outdoor variables were taken from Met office local weather stations [52] that were maximum 3 miles away from each study site.

2.2.2. Buildings

In this study, 32 NV classrooms were selected in eight primary schools with five criteria. 1. Selected schools are naturally ventilated since windows are the main source of ventilation in most schools in the UK. Furthermore, variations in temperature, relative humidity and indoor pollutants from mechanical ventilation and air-conditioning systems [50,51,53] can impact children's perception of IEQ. 2. Schools were selected in quiet areas with a considerable distance to the main road to not restrict window operation due to high background noise level as recommended by Building Bulletin 93: Acoustic Design of Schools to facilitate natural ventilation [54]. Selected schools have the regional Road Noise, LAeq 16h, less than 55 dB according to England Noise Map Viewer [55]. 3. Schools were also selected in low-polluted areas to not restrict window operation, as recommended by CIBSE TM 21: Minimising pollution at air intakes [56]. Selected schools have low Daily Air Quality Index (DAQI) according to Air pollution Forecast provided by the Met Office [57]. 4. Buildings were selected with different architectural features as buildings' design affects IEQ [58–61]. Classrooms and windows' architectural features are shown in Table 4; classroom area (50–70 m^2), volume (130–252 m^3), window area (0–8 m^2), number of windows (0–8) and the minimum height of windowsill (0.5–2.3 m). 5. Schools were selected among both renovated and existing buildings because buildings have different potentials for maintaining IEQ according to their age and design [3,21,61,62]. Schools 1, 2 and 6 are renovated (14 classrooms) and the rest 18 classrooms are not renovated.

Table 3
Descriptive statistics of outdoor physical variables during non-heating and heating seasons.

Mode	Variable	Minimum	Maximum	Mean	Std. Deviation
Non-heating	Tout	11.50	24.90	18.15	3.67
	Vout	.80	7.00	3.26	1.66
	Hout	32.50	93.00	67.91	17.8
Heating	Tout	3.50	14.20	7.84	2.90
	Vout	.80	6.00	2.85	1.66
	Hout	52.00	92.00	76.26	10.35

Fig. 2 and Fig. 3 show the interior and exterior of one of the renovated classrooms in school 1. This classroom has 8 operable windows designed at two levels and sizes with a total area of 8 m^2, Table 4.

2.2.3. Occupants

To study children's comfort based on IEQ, it is significant to select an age group that has a good understanding of questionnaire structure and indoor environment. Among primary school students, children in their late middle childhood (9–11 YO) rather than their peers in early middle childhood (6–8 YO) were selected as the main respondents of this study because of their more developed literacy skills, cognitive abilities [63] and attention span [64]. They evaluate facts better [64], which results in data validity and consistency of findings [63]. The gender ratio of surveyed girls (51%) and boys (49%) is approximately the same that can reduce bias and increase the credibility of results [65].

2.3. Data acquisition

2.3.1. Sensation votes

To obtain children's sensation votes on the thermal environment, IAQ, visual environment and overall comfort, the study has applied a questionnaire that was developed in an earlier study by authors [65]. Table 5 includes sensation questions with their scales and coding. The validity and reliability of all questions were tested through different methods including monitoring answer-process, statistical tests, observations, cross-checking, comparing responses and calculating mean and standard deviations, which are explained in details in an earlier study by authors [65].

Children were usually asked to fill out the paper-based questionnaire at the end of morning and afternoon sessions because the end of sessions has the poorest conditions in terms of IAQ [66]. In total, questionnaires were filled out on 52 different morning and afternoon sessions. Through transverse sampling, 805 children on 32 distinct days throughout one year were surveyed, resulting in collecting 1359 questionnaires as can be seen in Table 6.

2.3.2. Environmental variables

Environmental variables affecting IEQ and comfort were recorded at 5-min intervals, however, environmental variables that were recorded at the time of children's filling out the questionnaire were evaluated in this study. Air temperature, radiant temperature, humidity and air speed were recorded by multi-functional SWEMA equipment and standalone data loggers, CO_2 levels by TGE-0011 CO_2 meters and light levels by Light Meters. Details of the equipment including their range, resolution and accuracy are provided in Table 7. Measurement station was located away from sun patches and main airflows at a height of 1.1 m as recommended by ISO 7726 [67]. Calibrated light meters measured illuminance level on students' working desk when they were filling out the questionnaire. Equipment was placed within the vicinity of children's desks without impairing their visual access. The instruments were set up in the classrooms before children's arrival in the morning so that instruments acclimatize to the classrooms' indoor environment before reading [44]. Time-lapse cameras were installed inside the classrooms to record the state of windows, blinds and doors at 5-min intervals.

2.4. Analysing Regression Approach

The importance of this study is evaluating overall comfort based on IEQ using regressions on a large database obtained from field studies

Table 4
Classrooms' architectural features.

Mode	Date	General		Classroom			Window Design					W Operation	Blind Type	Exterior Door
		No.	Floor	Orientation	Area	Vo[1]	WA[2]	NW[3]	W Type	Ventilation	MHW[4]			
Non-heating	**July and Sep 2017**	**1.1**	First	NE	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre opening	1	Manually	Roller shades	No
		1.2	First	SW	60		8	8			1			No
		1.3	First	SW	60		8	8			1			No
		1.4	First	SW	60		8	8			1			No
		1.5	First	NE			8	8			1			No
		2.6	First	NW	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre openings	1	Manually	Roller shades	No
		2.7	First	SE	60		8	8			1	Manually		No
		2.8	First	SE	60		8	8			1	Manually		No
		2.9	First	NW	60		8	8			1	Manually		No
Heating	**Oct & Nov 2017**	**3.10**	Ground	S &W	65	227	2	5	Top-hung outward	Single-sided	1.7	Manually	Rollers	Yes
		3.11	Ground	S &W	70	245	2.2	6		Double-sided	1.6	Manually	Vertical blind	No
		3.12	First	NW	60	192	2.5	5		Single-sided	2.6	With handle		No
		4.13	Ground	W	50	130	0.5	2	Top-hung outward	Single-sided	1.8	Manually		Yes
		4.14	Ground	W	60	156	0.5	2			1.8	Manually		Yes
		4.15	Ground	No W	50	175	0	0	–	No opening	–	–	–	No
	Jan and Feb 2018	**5.16**	First	SW, SE	55	137	5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	Vertical blinds	No
		5.17	First	SW	55		5.7	8			0.5	Manually		No
		5.18	First	SW & NW	55		5.7	8			0.5	Manually		No
		5.19	Ground	SW	55		5.7	8			0.5	Manually		Yes
		5.20	Ground	SW & NW	55		5.7	8			0.5	Manually		Yes
		6.21	First	SE	60	168	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	Roller shades	No
		6.22	First	SE	60		1.8	4			2.3			No
		6.23	First	SE	60		1.8	4			2.3			No
		6.24	First	SE	60		1.8	4			2.3			No
		6.25	First	SE	60		1.8	4			2.3			No
Non-heating	**April/May 2018**	**7.26**	Ground	SE & SW	70	252	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	Vertical blinds	No
		7.27	Ground	SE & SW	55	137	3.3	3		Single-sided	1.65	Manually		Yes
		7.28	First	NE & NW	55	137	5.4	6		Double-sided	1.6	Manually		No
		8.29	Ground	NE	60	150	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	Internal roller shades	Yes
		8.30	Ground	NE	60	150	2.2	4			1.4	Manually		Yes
		8.31	Ground	NW	55	137	2.2	4			1.4	Manually		Yes
		8.32	Ground	NW	55	137	2.2	4			1.4	Manually		Yes

1 = Volume(m3)- 2 = Window Area (m2)- 3 = Number of Windows- 4 = Minimum Height of windowsill (m)

Fig. 2. Interior of one of the renovated classrooms in school 1.

Fig. 3. The exterior of one of the renovated classrooms in school 1.

Table 5
Sensation questions are taken from the questionnaire developed and validated by authors [65].

Comfort in Classrooms-Pupil Questionnaire				
1. How do you feel now?				
Cold (−2)	Cool (−1)	OK (0)	Warm (+1)	Hot (+2)
2. How is the air in the classroom now?				
Very fresh (1)	Fresh (2)	OK (3)	Stuffy (4)	Very Stuffy (5)
3. The light in my classroom is … now.				
Much (1)	Enough (2)	OK (3)	Not Enough (4)	Little (5)
4. Do you feel comfortable now?				
I am comfortable (1)	I am a little comfortable (2)	I am not comfortable (3)		

during one whole year. In this study, the combination of both environmental variables and sensation votes is employed to assess overall comfort.

Multiple Linear Regression: Regression produces a line of best fit by minimising the RSS (residual sum of squares) which is the difference between an observed Y and the predicted Y by the model [68]. Multiple regression models describe how a single dependent variable depends linearly on several predictor variables [69]. In this study, multiple linear regression analysis is used to achieve the explained variance for overall comfort. The values of the slopes in multiple regression depend on the units of dependent variables [69]. The units of dependent variables are different in this study (physical variables and sensation votes) which according to Bremer (2012) [69] makes it difficult to compare slopes with each other within the same model and across different models. To compare slopes, Bremer (2012) advises that it is important to scale regression coefficients (make them unit less), called standardized regression coefficients [69]. To specify which variables should be used in the multilinear regression model, Spearman correlation tests were run. Spearman's correlation is a non-parametric statistical measure for the strength of the relationship between paired data, used for ordinal/interval and skewed data [68,70–72].

Binary Logistic Regression: Logistic regression investigates the relationships between a categorical outcome variable and one or more continuous predictor variables and it leads to a model for predicting the probability of the event happening [73]. In this study, to estimate the probability of having uncomfortable votes, binary logistic regression is used. The data were analysed using the Statistical Package for Social Science (SPSS) [74].

Table 6
The number of schools, classrooms and children observed.

School Number	Date	Number of classrooms	Number of surveyed & observed children	Number of collected questionnaires from morning and afternoon
School 1	17–21 July 2017	5	130	203
School 2	21–27 September 2017	4	110	194
School 3	29–31 October 2017	3	65	112
School 4	21–24 November 2017	3	85	111
School 5	29 Jan-02 Feb 2018	5	145	285
School 6	12–16 Feb 2018	5	85	135
School 7	17–19 April 2018	3	80	162
School 8	22–25 May 2018	4	105	157
Total	**July 2017-May 2018**	**32**	**805**	**1359**

2.5. Evaluating IEQ against standards

In this study, classrooms' environmental conditions are evaluated against values recommended by following standards on IAQ, thermal comfort and visual comfort.

- For optimal operative temperature, results of an earlier study by authors [40] show that children's comfort temperature ($T_{C(children)}$) is 1.9K and 2.8K lower than comfort temperature recommended by European standard EN 15251 [66] during non-heating and heating seasons, respectively. The acceptable range of thermal comfort temperatures can be extended by ±2 for Category I Buildings according to European standard EN 15251:2007 [66].
- For optimal IAQ, American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard 62 recommends CO_2 level of 1000 ppm [75]. Similarly, EN 13779:2007 [76] recommends CO_2 levels below 1000 ppm for Categories I and II buildings.

Table 7
Details of the measuring equipment.

Probe	Variables	Meas. Range	Resolution	Accuracy
SWEMA	Humidity and air temperature	0 to 100 %RH, −40 to +60 °C	0.1% RH 0.1 °C	±0.8 %RH at 23 °C ±0.3 °C at 23 °C
	Air velocity and Air temperature	0.05–3.0 m/s at 15–30 °C, +10 to +40 °C	1.1 m/s 0.1 °C	±0.04 m/s at 0.05–1.00 m/s, ±4% read value at 1.0–3.0 m/s
	Radiant temperature (Ø globe: approx.150 mm)	0 to +50 °C	0.1 °C	±0.1 °C
Data Logger	Temperature	−35 to +80 °C	0.1 °C	±0.3 °C
	Humidity	0 to 100 %RH	0.5% RH	±0.2 %RH
TGE-0011	CO_2	0–5000 ppm	1 ppm	50 ppm
Light Meter	Light level	0 to 50000 Lux/Fc	0.1 Lux/Fc	±5% ± 10d (<10000Lux) ±10% ± 10d (>10000Lux)

- For optimal humidity and air speed, European standard EN 15251 recommends humidity range of 30–50% and maximum air velocity of 0.15 m/s for Category I buildings [66].
- For optimal light level, BS EN 12464–1:2011 recommends minimum light level of 300 lx in classrooms and tutorial rooms and 500 lx in art classrooms [77], which is also reproduced by The Society of Light and Lighting, CIBSE [78]. Boyce and Raynham (2009) in SLL Lighting Handbook state that the average illuminance should not exceed 300 lx for UGR = 13, 600 lx for UGR = 16 and 1000 lx for UGR = 19 [79]. Unified Glare Rating (UGR) values typically range from 13 to 30, with lower values providing more comfort [79]. To keep UGR values below 16 for having higher comfort, acceptable light levels are considered between 300 lx and 600 lx in this study.

2.6. Overview of the recorded data

To characterize classrooms' indoor environment quality (IEQ), average environmental variables at the time of filling out questionnaires including operative temperature (T_{op}), Air velocity (V = m/s), Humidity (RH%), CO_2 concentration levels (ppm) and average light levels (lx) are presented in Table 8 for non-heating and heating seasons.

Among surveyed children, 698 of children are comfortable, 472 of children are a little comfortable and 189 of children are not comfortable, Fig. 4.

3. Results and analysis

For the aim of this study, three main steps are followed; 1) proportion of comfort votes by IEQ aspects, 2) modelling comfort votes (multilinear regression model) and 3) Predicting probability of having uncomfortable votes (binary logistic regression).

3.1. Proportion of comfort votes by IEQ

The study has presented the frequency of comfort votes in different categories of Thermal Sensation Votes (TSVs), Fig. 5, Air Sensation Votes (ASVs), Fig. 6, and Visual Sensation Votes (VSVs), Fig. 7. The study classifies sensation votes into two main groups; corresponding to more

Table 8
Descriptive statistics of indoor environmental variables during non-heating and heating seasons.

Seasons		Minimum	Maximum	Mean	S.D.
Non-heating	T_{op}(°C)	19.0	28.1	24.2	2.1
	RH%	38.3	66.6	50.9	7.8
	V(m/s)	0.00	0.72	0.10	0.14
	CO_2 levels (ppm)	662	3277	1180	488
	Lux (lx)	186	1225	467	237
Heating	T_{op}(°C)	18.9	26.8	22.8	1.7
	RH%	25.8	53.4	37.3	7.3
	V(m/s)	0.00	0.30	0.06	0.07
	CO_2 levels (ppm)	842	2106	1310	351
	Lux (lx)	230	1130	527	253

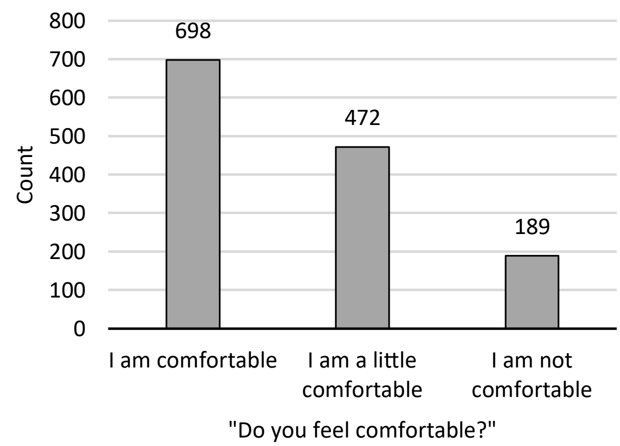

Fig. 4. Frequency of comfort votes among surveyed children.

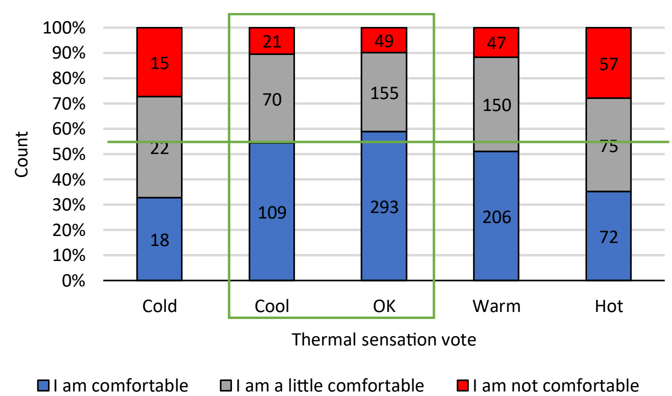

Fig. 5. Frequency of comfort votes in different categories of TSVs.

than 55% (more than half) of overall comfort votes or less than 55% of them in each category. Among TSVs, only Cool (55%) and OK (59%) votes accommodate more than 55% of comfortable votes, Fig. 5.

Among ASVs, only Very fresh (61%) and Fresh (67%) votes accommodate more than 55% of comfortable votes, Fig. 6. Among VSVs, only Enough (59%) votes accommodate more than 55% of comfortable votes, Fig. 7.

The study compares frequency (%) of comfort votes between sensation groups based on the above classification. When sensation votes correspond to more than 55% of comfortable votes, [TSVs = Cool (−1), OK (0)] or [ASVs = Very Fresh (1), Fresh (2)] or [VSVs = Enough (2)], sensation votes are named (Y) for Yes. When sensation votes receive less than 55% of comfort votes [TSVs = −2, 1, 2] or [ASVs = 3, 4, 5] or [VSVs = 1, 3, 4, 5], the scales are named (N) for No.

The study outlines eight groups, which is the result of combining Y

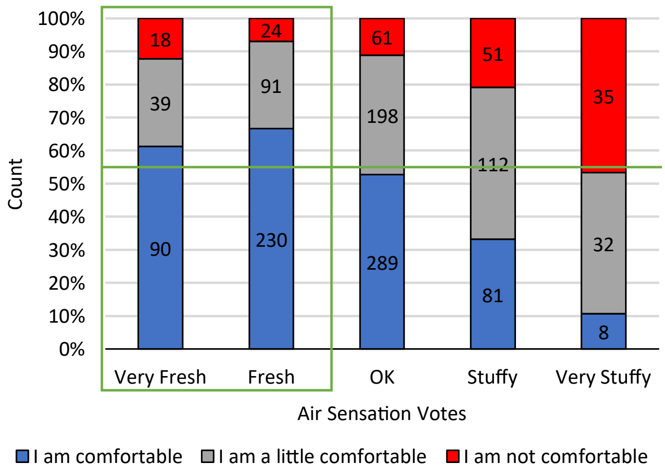

Fig. 6. Frequency of comfort votes in different categories of ASVs.

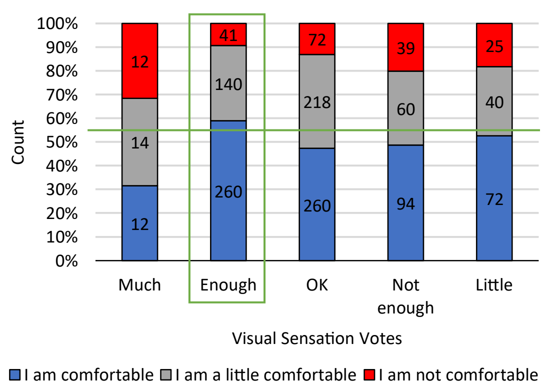

Fig. 7. Frequency of comfort votes in different categories of VSVs.

and N categories in 3 sensation groups (TSVs, ASVs and VSVs), Fig. 8. The order of eight groups in Fig. 8 is presented based on the frequency (%) of comfortable votes, uncomfortable votes, and the difference between these two. As can be seen in Fig. 8, groups 1–4 show uncomfortable votes below 10% and groups 1–7 suggest uncomfortable votes below 20%. In groups 1–4, at least two sensation votes are acceptable, however, in groups 5–8, only one or none of the sensation votes are acceptable. It can be argued that considering 20% uncomfortable as the criteria for overall comfort can be an overestimation as it can let two aspects of the IEQ being unacceptable. Therefore, this study suggests the criteria for permissible uncomfortable votes at 10%.

To find out how many votes would benefit from keeping uncomfortable votes below 10%, the study presents the frequency (N) of votes in each group, Fig. 9. By reducing uncomfortable votes from 20% (groups 1–7) to 10% (groups 1–4), uncomfortable votes would drop from 113 to 35 that corresponds to a reduction of 69% in uncomfortable votes, Fig. 9. Primary schools are occupied by sensitive young children [66] who have physical and physiological differences with adults [50, 80–83]. This makes them more vulnerable and less resistant than adults to poor environmental conditions [3,28,84–87], therefore, it is significant to reduce the number of uncomfortable children.

It should be highlighted that in groups 1, 3 and 4 in Fig. 8, one of the sensation votes is unacceptable, however, the percentage of uncomfortable children is still below 10%. This shows that dissatisfaction with one aspect of the indoor environment does not necessarily produce overall discomfort with the environment, as suggested by Humphreys (2005) [88]. Humphreys (2005) advised that acceptable aspects of IEQ can compensate for unacceptable aspects [88].

Table 9 shows indoor physical parameters in groups 1–8. Average physical variables for group 2 with all acceptable sensation votes and uncomfortable votes below 10% are T_{op} = 22.2 °C, CO_2 level = 1010 ppm, lux = 587 lx, V = 0.10 m/s and H = 43.5% which are close to values suggested by standards in 2.5. Chapter of the paper. An earlier study by authors [40] suggests $TC_{(children)}$ at 20.9 °C during non-heating seasons and at 20.2 °C during heating seasons. Therefore, the approximate operative temperature of 23 °C (20.9 ± 2) is the upper limit of children's thermal comfort band [40] which is close to the average T_{op} of 22.2 °C in groups 2.

3.2. Modelling comfort votes

Individual Aspects of IEQ: This part of the study explores the relationship between comfort votes as the dependent variable with individual aspects of IEQ as the independent variables. Spearman correlations, regression equations and R^2 values for potential variables are presented in Table 10. According to Table 10, TSVs, ASVs, VSVs, operative temperature (T_{op}), CO_2 and air speed (V) are correlated with overall comfort, however, changes in overall comfort are mostly explained by ASVs and T_{op} due to higher R^2 values. ASVs account for 8% of changes in overall comfort (R^2 = 0.08) and T_{op} accounts for 3% of comfort votes (R^2 = 0.03), Table 10. The R^2 value shows the proportion of the variation in the dependent variable explained by the model [71, 72].

Integrated Aspects of IEQ: To find out how integrating correlated variables affect overall comfort, the multilinear regression model is run. Both Unstandardized Coefficients for suggesting acceptable limits of

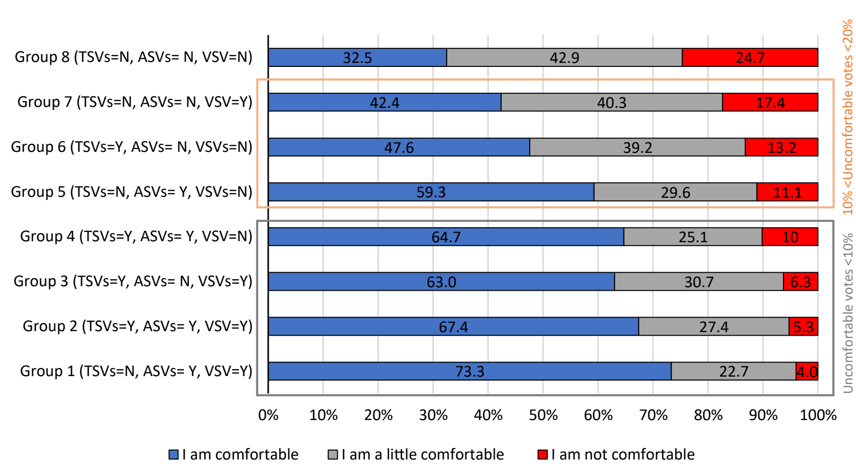

Fig. 8. Frequency of comfort votes (%) in eight different sensation groups.

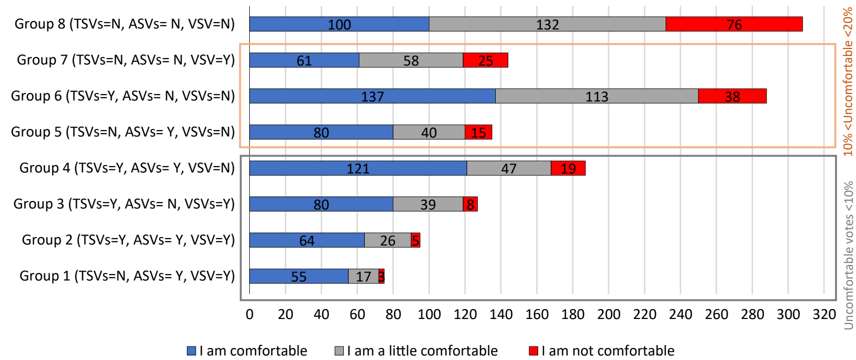

Fig. 9. Frequency of comfort votes in eight different sensation groups.

Table 9
Physical parameters in groups 1-8.

Categories	T_{op} (°C)	CO_2	Lux (lx)	V (m/s)	H (%)	Uncomfortable (%)	
Group 1 (TSVs = N, ASVs = Y, VSV=Y)	23.10 ≈ 23	1177	640	0.11	41.14	4	✓
Group 2 (TSVs = Y, ASVs = Y, VSV=Y)	22.20 ≈ 22	1010	587	0.10	43.51	5.3	✓
Group 3 (TSVs = Y, ASVs = N, VSVs = Y)	22.90 ≈ 23	1300	557	0.07	42	6.3	✓
Group 4 (TSVs = Y, ASVs = Y, VSV=N)	23.30 ≈ 23	1190	475	0.08	45.74	10	✓
Group 5 (TSVs = N, ASVs = Y, VSVs = N)	23.9 ≈ 24	1180	444	0.08	46.86	11.1	×
Group 6 (TSVs = Y, ASVs = N, VSVs = N)	23.7 ≈ 24	1278	423	0.08	46.16	13.2	×
Group 7 (TSVs = N, ASVs = N, VSV=Y)	23.6 ≈ 24	1263	603	0.06	41.57	17.4	×
Group 8 (TSVs = N, ASVs = N, VSV=N)	24.0 ≈ 24	1265	443	0.08	44.59	24.7	×

dependent variables and Standardized Coefficients for comparing slopes are presented in Table 11.

Variables that are not correlated with comfort votes in Table 10 such as tiredness, light level and humidity are not considered in the multilinear regression model. Results of the multilinear regression model in Table 11 shows that after integrating all variables, the correlation of ASVs and T_{op} with comfort votes remain significant. Comparing Tables 10 and 11 shows that when variables are integrated, their correlations and regressions change because independent variables affect each other or are controlled by each other. The standardized multilinear regression model is presented in Equation (1):

$$Comfort = 0.28 * ASVs + 0.12 * T_{op} \qquad R^2 = 0.11 \tag{1}$$

(ASVs = 1–5, T_{op} = 19–28 °C).

Range of operative temperature is chosen based on the minimum and maximum operative temperatures in this study, which is 19–28 °C.

The regression coefficient is the rate at which changes in the independent variable affect the dependent variable. Therefore, for a unit change in ASVs and T_{op}, comfort votes change by 0.28 and 0.12, respectively. The coefficient value is more than two times higher for ASVs (0.28) than that for T_{op} (0.12), which suggests ASVs have a more significant impact on overall comfort than T_{op}.

Fig. 10 shows comfort points based on the unstandardized multilinear regression model developed in this study (Comfort = 0.20*ASVs+0.041*T_{op}, Table 11). Although comfort votes as the dependent variable should be shown on the y-axis, they are shown on the x-axis to see their relationship with two independent variables (ASVs and T_{op}). According to Fig. 10, when children perceive air to be fresh and when the operative temperature is lower, overall comfort is higher. As

Table 11
Coefficients in the multilinear regression between comfort votes and individual aspects of IEQ.

Independent Variables in multilinear regression		Unstandardized Coefficients	Standardized Coefficients	Sig.
(Constant)		.171		.502
Sensation	TSV	-.003	−0.004	.879
	ASV	.200	0.284	.000
	VSV	.029	0.041	.135
Physical variables	T_{op} (°C)	.041	0.116	.000
	CO_2 (ppm)	.000	−0.073	.10
	V (m/s)	.116	0.018	.512
Multilinear regression Model		Comfort = 0.28*ASVs+0.12*T_{op}, (R^2 = 0.11)		

Table 10
The correlation and regression of comfort votes with individual aspects of IEQ.

Independent Variables		"Do you feel comfortable?"			
		Spearman Correlation Coefficient	Sig. (2-tailed)	Regression Equation	R^2 value
Sensation	TSV	.102**	0.000	Comfort = 0.064*TSV+1.602,	R^2 = 0.008
	ASV	.280**	0.000	Comfort = 0.197*ASV+1.07,	R^2 = 0.08
	VSV	.063*	0.020	Comfort = 0.038*VSV+1.51,	R^2 = 0.003
	Tiredness	0.035	0.199	–	–
Physical variables	CO_2 level (ppm)	-.062*	0.035	Comfort = −0.0001*CO_2+1.8,	R^2 = 0.004
	T_{op} (°C)	.122**	0.000	Comfort = 0.056*T_{op}+0.307,	R^2 = 0.03
	Lux (lx)	0.000	0.986	–	–
	V (m/s)	.094**	0.001	Comfort = 0.033*AS+1.623,	R^2 = 0.000
	RH (%)	0.020	0.452	–	–

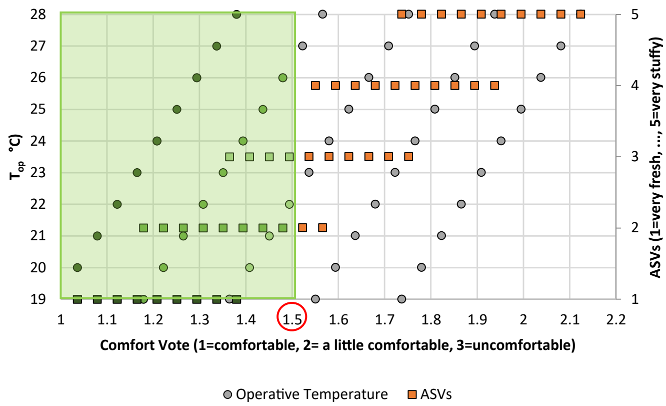

Fig. 10. The relationship between ASVs, T_{op} and comfort points by the developed model.

1.5 on the x-axis is the transition point from 'comfortable votes' to 'a little comfortable' votes, points below 1.5 are classified as those that can provide overall comfort, seen in the green box in Fig. 10.

3.3. *Estimating the probability of having uncomfortable votes*

To estimate the probability of having uncomfortable votes, the binary logistic regression model is used. To run binary models, comfort votes are classified into 'Comfortable' and 'Uncomfortable' groups. Regression coefficients and their significance for the logistic model in Table 12 show that ASVs and T_{op} are correlated with overall comfort, as suggested earlier in the multilinear regression model.

The model to estimate the probability of having uncomfortable votes can be found in Equation (2):

$$Logit\ (PD) = 0.77^{*}ASVs + \ 0.30^{*}T_{op} - 11.16 \quad (R^2 = 0.14) \tag{2}$$

Where

$$PD = \left(\frac{e^{\left(0.77^{*}ASVs+\ 0.30^{*}T_{op}-11.16\right)}}{1 + e^{\left(0.77^{*}ASVs+\ 0.30^{*}T_{op}-11.16\right)}}\right)^{*}100 \tag{3}$$

PD: Probability of having uncomfortable votes, ASVs = 1–5, T_{op} = 19–28 °C.

Fig. 11 shows the probability of having uncomfortable votes by logistic regression model when ASVs range from '1–5' and T_{op} ranges from '19–28 °C'. According to Fig. 11, the probability of having uncomfortable votes is higher when children perceive air to be stuffy and when T_{op} is higher. Green points inside the green box in Fig. 11 show conditions under which the probability of having uncomfortable votes is kept below 10%.

Table 12
Variables in the logistic regression equation.

Independent Variables in Logistic Regression	Coefficients for dependent variables: "Do you feel comfortable?"	
	Coefficients (B)	Sig.
TSV	0.035	0.697
ASV	0.766	0.000
VSV	0.160	0.070
T_{op} (°C)	0.299	0.000
CO_2 (ppm)	0.000	0.129
V (m/s)	−0.530	0.678
Constant	−11.165	0.000
Developed Logit (PD)	Logit (PD) = 0.77*ASVs+ 0.30*T_{op}-11.16 (R^2 = 0.14)	

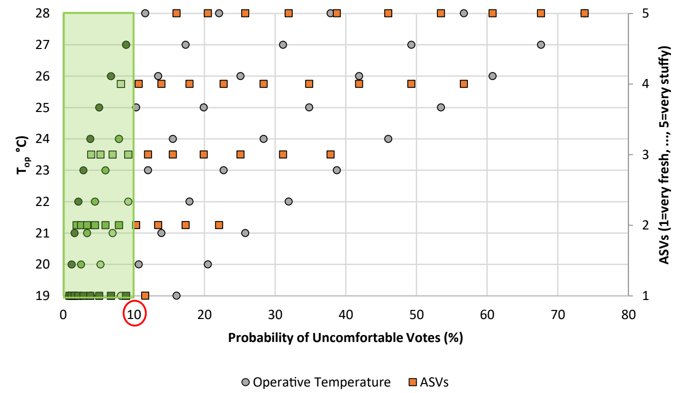

Fig. 11. The probability of having uncomfortable votes by the developed model.

4. Discussion

4.1. *Comparing two models*

Comparing multi-linear and logistic regression models show two main findings in common. 1) Both models show that changes in overall comfort and uncomfortable votes are explained more significantly by sensation votes (ASVs) than by physical parameters (T_{op}). The study by Fransson et al. (2007) supports that the subjective ratings are significantly better than objective indicators at predicting overall rated indoor comfort [1]. 2) Both models show that ASVs and T_{op} contribute to overall comfort, with ASVs having a more significant impact. An earlier review of educational studies in the Introduction chapter suggests that the most important aspects of IEQ impacting comfort are thermal environment [15,34,35] and IAQ [20,33,36]. Humphreys (2005) confirms that satisfaction with air quality contributes strongly to overall satisfaction, therefore, an improvement in IAQ would yield considerable improvement in overall comfort [88]. An earlier study by authors on the same subjects shows that improved perception of indoor air quality results in higher overall comfort votes [89].

Dorizas et al. (2015) confirm that temperature is a crucial indicator of students' satisfaction and comfort of the indoor environment [10]. Huang et al. (2012), suggest that satisfaction with temperature has one-vote veto power over the overall satisfaction of the indoor environment [90]. Apart from the direct impact of T_{op} on overall comfort, it can affect ASVs and consequently overall comfort. Previous studies have supported that occupants' perceived IAQ is affected by T_{op} and lower temperatures improve perceived IAQ [10,89,91–95]. Another study by authors shows that most favourable ASVs are given when children feel 'cool' and have 'as it is' preference [89].

4.2. *Linking the results of two models*

To recommend acceptable ranges of ASVs and T_{op}, points below 1.5 in the multilinear model (Fig. 10, Highlighted in green) and points having uncomfortable votes below 10% in the logistic regression model (Fig. 11, Highlighted in green) are compared in Table 13. To meet the criteria of both models, ASVs and T_{op} should be in the following ranges: 1) [ASV = 1 and T_{op} = 19–27 °C], 2) [ASV = 2 and T_{op} = 19–24], and 3) [ASV = 3 and T_{op} = 19–22].

- The ranges show that better perception of IAQ makes up for higher temperatures. Conversely, when children's perception of IAQ deteriorates, acceptable temperatures are lower and more limited to still provide overall comfort. In other words, lower temperatures make up for deteriorated perceived IAQ as supported in several other studies [10,89,91–95].

Table 13
Linking ranges of ASV and T_{op} for multi-linear and binary logistic models.

No	(Criterion 1): ASVs and T_{op} for Comfort Model<1.5			(Criterion 2) ASVs and T_{op} for PD<10%			Meeting Criteria 1 and 2	
	ASVs	T_{op} (°C)	Comfort Model	ASVs	T_{op} (°C)	Probability	ASVs	T_{op}
1	**1 = very fresh**	19–28	1.0–1.38	1 = very fresh	19–27	1–9%	1	19–27
2	**2 = fresh**	19–26	1.2–1.48	2 = fresh	19–24	2–8%	2	19–24
3	**3 = OK**	19–22	1.4–1.5	3 = OK	19–22	4–9%	3	19–22
4	**4 = Stuffy**	–	–	4 = Stuffy	19	8%	–	–

- As seen in Table 13, the only acceptable ASVs are 'very fresh, fresh and OK', however, when ASVs are 'OK', acceptable T_{op} is limited to 19–22 °C. Operative temperatures in this range are suggested as the comfort temperature in several other studies [20,25,40,51,96,97].
- As can be seen in Table 13, when ASVs are 'stuffy' or 'very stuffy', children are not comfortable, suggesting that extremely unacceptable ASVs (i.e. 'stuffy or very stuffy') result in uncomfortable votes. This finding is supported by Nagano and Horikoshi (2005) that claim when one factor is extremely uncomfortable in the environment (i.e. too hot or too noisy), the impact of other factors may be excluded [29] and the occupants will express discomfort [2,29]. Similarly, Tahsildoost and Zomorodian (2018) state that occupants' high dissatisfaction with one parameter can cause respondents' overall discomfort [34].
- As can be seen in Table 13, the maximum operative temperature at which overall comfort can be provided is 27 °C if children's perception of IAQ is 'very fresh'. Similarly, the study by Catalina and Iordache, (2012) in schools shows that the predicted overall IEQ index is sensitive to T_{op} <18 °C and T_{op} >28 °C [37]. Yet, it is recommended to keep operative temperatures close to children's thermal comfort temperatures for its impact on perceived indoor air quality [89], energy consumption [20] and productivity [98]. An earlier study by authors shows that by keeping $CO_2 < 1000$ ppm and T_{op} within children's thermal comfort band, ASVs are improved by 43% [89]. Comfort temperatures impact energy consumption especially during winter as children's comfort temperature is lower than that for adults [40]. On the impact of operative temperatures on productivity, the study by Wargocki and Wyon (2007) on 10–12 years old children shows that the results of numerical and language-based tests were significantly improved when the temperature was reduced from 25 °C to 20 °C [98].

4.3. Classrooms' environmental conditions against recommended values

To generalize the results of this study to other studies, it is important to reflect conditions under which the models were developed. Table 14 shows indoor physical variables in each classroom and their evaluation against recommended values by standards in chapter 2.5.

Table 14 shows that 8 classrooms meet acceptable CO_2 levels, 12 classrooms meet acceptable operative temperatures, 20 classrooms meet acceptable humidity ranges, 24 classrooms meet acceptable light levels and 30 classrooms meet acceptable air speeds. It can be suggested that the comfort model has reflected the less acceptable aspects of IEQ, which are IAQ and thermal environment in this study and has not reflected the more acceptable aspect which is lighting environment in this study.

Table 14
Indoor physical variables in each classroom and their comparison with recommended values by standards.

No.	CO_2	$CO_2 < 1000$	T_{op}(°C)	Comfort Band	T_c-2<T_{op} < T_c+2	H (%)	30<H < 50	Lux (lx)	300<lx < 600	V (m/s)	V < 0.15
1.1	910	✓	25.5	22 ± 2	×	40.70	✓	436	✓	0.04	✓
1.2	1063	×	27.6	22.3 ± 2	×	42.80	✓	589	✓	0.15	✓
1.3	731	✓	26.5	22.8 ± 2	×	61.10	×	502	✓	0.10	✓
1.4	719	✓	26.4	22.9 ± 2	×	61.45	×	650	×	0.13	✓
1.5	823	✓	25.4	22.9 ± 2	×	47.10	✓	408	✓	0.05	✓
2.6	1228	×	23.9	21.5 ± 2	×	59.65	×	384	✓	0.04	✓
2.7	1600	×	24.4	20.9 ± 2	×	61.90	×	331	✓	0.08	✓
2.8	1502	×	25.2	21.1 ± 2	×	53.15	×	465	✓	0.15	✓
2.9	1431	×	25.3	21.2 ± 2	×	56.40	×	388	✓	0.15	✓
3.10	989	✓	22.5	20.6 ± 2	✓	31.90	✓	661	×	0.03	✓
3.11	1114	×	24.0	20.5 ± 2	×	44.30	✓	305	✓	0.06	✓
3.12	1438	×	21.8	20.4 ± 2	✓	53.40	×	520	✓	0.06	✓
4.13	1511	×	24.7	20.3 ± 2	×	42.50	✓	468	✓	0.04	✓
4.14	861	✓	23.5	20.4 ± 2	×	49.70	✓	652	×	0.02	✓
4.15	1260	×	24.1	20.5 ± 2	×	38.60	✓	555	✓	0.05	✓
5.16	1826	×	22.3	20.3 ± 2	✓	49.20	✓	646	×	0.03	✓
5.17	1103	×	21.2	20.4 ± 2	✓	34.48	✓	707	×	0.01	✓
5.18	1298	×	19.5	20.3 ± 2	✓	33.50	✓	547	✓	0.03	✓
5.19	1016	×	23.4	20.3 ± 2	×	35.71	✓	510	✓	0.20	×
5.20	1316	×	22.8	20.3 ± 2	×	35.55	✓	309	✓	0.04	✓
6.21	1079	×	25.0	20 ± 2	×	26.79	×	655	×	0.15	✓
6.22	2054	×	22.8	20 ± 2	×	37.90	✓	386	✓	0.00	✓
6.23	1010	×	21.8	20 ± 2	✓	26.80	×	554	✓	0.02	✓
6.24	1316	×	20.8	20.1 ± 2	✓	33.90	✓	800	×	0.03	✓
7.26	1075	×	22.9	21.4 ± 2	✓	42.82	✓	338	✓	0.02	✓
7.27	686	✓	23.4	21.5 ± 2	✓	42.17	✓	929	×	0.00	✓
7.28	1530	×	22.5	20.3 ± 2	×	44.10	✓	321	✓	0.04	✓
8.29	1202	×	23.5	20.8 ± 2	×	45.55	✓	331	✓	0.03	✓
8.30	810	✓	19.6	20.7 ± 2	✓	51.30	×	396	✓	0.46	×
8.31	3277	×	22.8	20.9 ± 2	✓	52.90	×	400	✓	0.01	✓
8.32	1123	×	21.9	20.9 ± 2	✓	51.50	×	463	✓	0.01	✓
Overall	**8 Classrooms ✓**		**12 Classrooms ✓**			**20 Classrooms ✓**		**24 Classrooms ✓**		**30 Classrooms ✓**	

4.4. Comfort model not reflecting visual environment

Three main reasons can be argued for the comfort model not reflecting visual environment. First, 24 out of 32 (75%) classrooms provide acceptable visual environments while it is suggested that the model does not reflect the more acceptable aspects of IEQ. Second, visual environment is the least important aspect of IEQ, as supported in several other studies [5,9,11,35,88,90,99]. This can be explained by subjects being less sensitive to illuminance changes [90] due to physiological adaptations [90,100]. The study by Ghita and Catalina, (2015) shows that children can adapt extremely well to their environment as majority of respondents declared that illuminance levels were adequate despite poor visual conditions in the schools [20]. The study by Huang et al. (2012), shows that the satisfaction of light level does not have one-vote veto power over the overall satisfaction of the indoor environment [90]. In other words, even when light level is outside the acceptable range, it is still possible for the entire environment to be judged as acceptable [90]. Third, the study has examined one aspect of the visual environment which is related to the light level. However, visual environment is a subjective measure that can be affected by several other metrics such as glare [11,18,66,101] and distribution [11,18].

4.5. Variations in comfort model

The comfort model suggests that 11% of changes in overall comfort are explained by IEQ aspects, Table 11. The binary logistic model suggests that 14% of changes in uncomfortable votes are explained by IEQ aspects, Table 12. It should be noted that R-squares, even though small, indicate that the regression models have statistically significant explanatory power due to the large sample size ($N_{Respondents} = 805$ and $N_{Questionnaires} = 1359$). The *primary* reason for having small R^2 values can be related to interval (discontinuous) rating scales, with three-rating scales for comfort votes and five-rating scales for other sensation votes. The *secondary* reason for having small R^2 values can be related to other external factors that have not been identified and included in the statistical model. For example, type of work [95,102] and stress level [103] can impact children's perception of comfort and IEQ in schools. Humphreys (2005) confirms that some of the unexplained variations in comfort model can be explained by 'individual differences' and 'aspects not considered in the survey' [88].

It should be highlighted that proposing a universal comfort model that applies to all building types in different locations can be challenging. Several other studies confirm that developing an internationally valid index for assessing IEQ is not simple [14,20,37,88], mainly because the interaction and conflict between individual aspects of IEQ are difficult to consider [7,14,32]. Furthermore, the relative importance and weighting of the various aspects can differ from country to country [88], over time [20,88] and by space-type differences [14,20]. Mihai and Iordache, (2016) suggest that respondents' expectations of building performance, outdoor climate, region and education level can make the hierarchy of comfort aspects different from one building to another [33].

Despite these challenges, this study and previous studies have investigated overall comfort or IEQ index, mainly because IEQ index can be used by architects and engineers to evaluate and enhance comfort of a built environment [35], optimize building energy consumption versus IEQ [37], renovate existing buildings [33,104], rank the most important aspects of IEQ [20] and understand the IEQ condition at a glance [36]. Investigating the most influential factors on occupants' comfort suggests which building controls should be prioritized for designers. In this study, the highest priority should be given to controls that provide IAQ and thermal comfort.

4.6. Contextual factors in comfort model

To generalize the results of this study, it is significant to acknowledge the conditions under which this study was carried out.

- The study was carried out in the mild climate of the UK. For schools located in extreme climatic conditions, IEQ aspects could be prioritized differently in response to overall comfort.
- Schools were selected in quiet areas to not restrict window operations in this study. For schools located in busy areas, comfort model could be impacted by acoustic comfort.
- Schools were selected in low-polluted areas to facilitate window operations; therefore, the main pollution source is exhaled air by occupants and CO_2 concentrations in this study. For schools located in polluted areas, comfort model could be impacted by indoor air pollutants suggested by SINPHONIE project in Building Bulletin 101 [60].
- Selected schools are naturally ventilated to investigate the impact of adaptive behaviours on natural ventilation. For mechanically ventilated and mixed-mode buildings, the weight of IEQ aspects could be different.
- This study has examined one aspect of the visual environment which is related to the light level (lx). For studies that consider metrics on glare and distribution as well, the impact of visual comfort on IEQ and comfort could be different.
- This study was carried out on 9–11 years old children. For educational buildings occupied with adults, IEQ aspects could be ranked differently in relation to overall comfort.
- This study has focused on the data for the whole year. In models that are developed for different seasons, the weight of IEQ aspects could be different.

The results of this study can be generalized to studies carried out under the above conditions; however, results may not apply without caution to studies conducted under totally different conditions. It should be highlighted that comfort and IEQ models are context-based and need to be treated accordingly.

5. Conclusion

This study has investigated children's overall comfort within individual aspects of IEQ (thermal comfort, IAQ and visual comfort) in the naturally ventilated schools located in a mild climate with low background noise and pollution levels. This study highlights that the most important aspects of IEQ on overall comfort are ASV and T_{op}. IAQ and thermal environment should be considered together to keep overall discomfort below the permissible level of 10%, suggesting that the integration between IAQ and thermal comfort should receive certain consideration in school buildings. Due to the nature of learning that happens through various senses, it is advised to maintain individual aspects of IEQ. However, dissatisfaction with one aspect of IEQ does not necessarily result in overall discomfort unless the aspect is extremely unacceptable. Investigating the most significant factors on occupants' comfort suggests which building controls should be prioritized for designers. Therefore, controls that provide IAQ and thermal comfort should be given the highest priority in this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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